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ORIGINAL ARTICLE

A finite element study on stress distribution of two different attachment designs under implant supported overdenture

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KEYWORDS

Ball and socket attachment;
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Abstract *Objective:* This study aimed to evaluate stress patterns generated within implant-supported mandibular overdentures retained by two different attachment types: ball and socket and locator attachments.

Materials and methods: Commercial CAD/CAM and finite element analysis software packages were utilized to construct two 3D finite element models for the two attachment types. Unilateral masticatory compressive loads of 50, 100, and 150 N were applied vertically to the overdentures, parallel to the longitudinal axes of the implants. Loads were directed toward the central fossa in the molar region of each overdenture, that linear static analysis was carried out to find the generated stresses and deformation on each part of the studied model.

Results: According to FEA results the ball attachment neck is highly stressed in comparison to the locator one. On the other hand mucosa and cortical bone received less stresses under ball and socket attachment.

Conclusions: Locator and ball and socket attachments induce equivalent stresses on bone surrounding implants. Locator attachment performance was superior to that of the ball and socket attachment in the implants, nylon caps, and overdenture. Locator attachments are highly recommended and can increase the interval between successive maintenance sessions.

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1. Introduction

Fabrication of a complete mandibular denture that offers patient comfort, function, and esthetic harmony along with stability and retention remains one of the most challenging procedures in dental practice. Lack of sufficient retention of a complete mandibular denture is common, especially when compared with the excellent retention obtained with the maxillary counterpart (Epstein et al., 1999).

Edentulous patients with severely resorbed mandibles often experience problems with complete dentures, such as insufficient retention and stability during masticatory function (Eriksson et al., 1990). These issues alter muscular function, further destabilizing the denture (Kabcenell, 1971), which poses serious problems for prosthodontists and completely edentulous patients (Moghadam and Scandrett, 1979). An implant overdenture provides prosthesis stability and enables the patient to consistently reproduce centric occlusion (Jemt and Stalblad, 1986). Higher bite forces have been documented for mandibular overdentures on implants. The maximum occlusal force of a patient with dentures may improve 300% with an implant-supported prosthesis (Haraldson et al., 1988).

Forces applied to dental implants may be characterized in terms of five distinct, but related, factors: magnitude, duration, type, direction, and magnification (Misch, 2005). Load transfer at the bone–implant interface depends on: (1) loading type, (2) material properties of the implant and prosthesis, (3) implant geometry (length, diameter, and shape), (4) implant surface structure, (5) nature of the bone–implant interface, and (6) quality and quantity of surrounding bone (Geng et al., 2001). Most efforts have been directed at optimizing implant geometry to maintain a beneficial stress level in a variety of loading scenarios (Geng et al., 2001).

The concept of implant-supported overdentures (IODs) was developed to increase overdenture retention, stability, and support with the use of different attachment systems (Mohie Eldin, 1993). IODs have been shown to provide successful long-term outcomes, particularly when used to restore edentulous mandibles. Numerous studies have reported 5-year implant survival rates between 94% and 100% and high rates of patient satisfaction (Awad et al., 2003). Ball and socket attachments are used widely because of their low cost, ease of handling, minimal chairside time requirement, and possible applications with root- and implant-supported prostheses. This device type consists of a metal ball attachment and a female component retained frictionally over the male stud, and is incorporated into the denture resin (Preiskel, 1996; Budtz-Jorgensen, 1999).

The locator attachment, a universal-hinge resilient attachment, is indicated for use with overdentures retained completely or partially by endosseous implants. Locator attachments can replace existing ball abutments, particularly in patients who experience problems with rapid wearing of ball abutment components (Danesh-Meyer, 2009). Locator attachments have a rotational pivoting design, with the male component providing a resilient connection for the prosthesis with no resulting loss of retention. The retentive nylon male component remains completely in contact with the abutment socket, while the titanium denture cap has a full range of rotational movement over the male component (Chikunov et al., 2008). The use of locator attachments has become popular due to excellent retention, small device dimensions (especially height), and component durability.

Finite element analysis (FEA) has several advantages over other methods (e.g., strain gauge and photoelastic materials techniques), including precise modeling of complex geometries, ability to investigate the internal state of stress and easy model simulation (Chun et al., 2002). In a previous finite element based study (El-Taftazani et al., 2011) ball and locator attachments were compared where load was directly applied to the nylon caps, locator showed superior to ball attachments in terms of reducing stress on the implant body and supporting structures of IODs.

The aim of this study was to directly and quantitatively compare two types of resilient attachments; ball and socket and locator when supporting complete overdenture at canine regions using finite element analysis and be compressively loaded in the molar region.

Table 1 Number of nodes and elements in all meshed components.

	Locator attachment		Ball attachment	
	Nodes	Elements	Nodes	Elements
Overdenture	1,724	6,228	2,056	7,287
Mucosa	2,556	7,326	2,594	7,470
Nylon ring (cap)	5,825	27,031	2,388	10,264
Implant complex	46,893	244,131	56,922	317,994
Cortical bone	1,773	4,897	1,769	4,892
Cancellous (spongy) bone	8,313	29,451	8,307	29,486

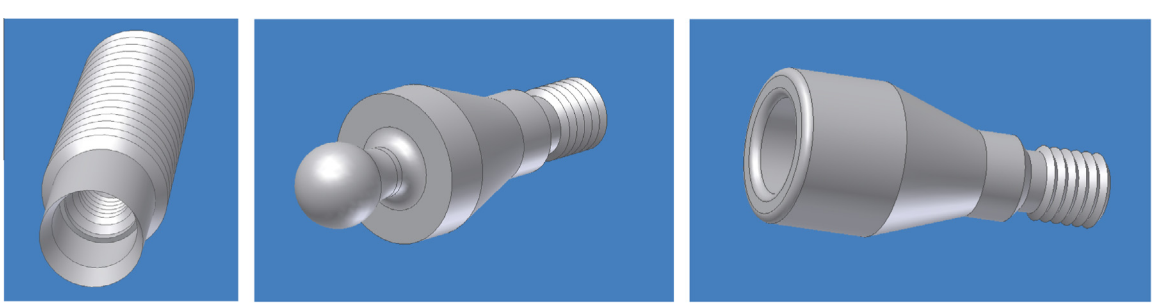

Figure 1 Implant, ball, and locator attachment models on autodesk inventor screen.

Table 2 Material properties used in the finite element model.

Material	Young's modules (GPa)	Poisson's ratio
Overdenture	2.70	0.35
Mucosa	0.01	0.40
Nylon ring (cap)	0.35	0.40
Implant complex	110.0	0.35
Cortical bone	13.70	0.30
Cancellous (spongy) bone	1.37	0.30

2. Materials and methods

FEA was used to simulate a clinical situation in which an edentulous mandible was restored with an overdenture retained by two implants placed in the approximate canine regions. Two solid 3D models were constructed (similar to Geng et al., 2008, example pp. 93-–114) to examine the use of ball and socket (model 1) and locator (model 2) attachments using general-purpose commercial CAD/CAM software (AutoDesk Inventor, ver. 8.0; Autodesk Inc., San Rafael, CA, USA).

The modeled implant complexes consisted of commonly available root-form threaded titanium dental implants (Zimmer Dental Inc., USA) with ball or locator attachments (Zest Anchors, Escondido, CA, USA). Each implant had a nominal diameter of 3.7 mm, length of 13 mm, and internal hex shape (width, 3.5 mm; Fig. 1), where, modeling software was used to ensure correct implant placement and angulation.

All the 3D model components (overdenture, mucosa, caps, ball and socket/locator attachment, cortical and cancellous bone) were exported in SAT file format (El-Anwar, 2009). Then these files were imported, assembled, and meshed after a set of Boolean operations using multipurpose finite-element software package (ANSYS, version 9.0; ANSYS Inc., Canonsburg, PA, USA). The bonded type simulates perfect osseointegration in which the implant and the surrounding compact bone are fully integrated that neither sliding nor separation in the implant–bone interface is possible. Meshing of these components into 3D solid brick elements (with three degrees of freedom and translation in main axis directions) (Kohnke, 1994) resulted in a huge number of nodes and elements on each component that are listed in Table 1. The unique physical properties of each component were uploaded to the finite element package, which determined components' material behavior under uniaxial loading. The material properties used in the current study, listed in Table 2, assumed isotropic homogeneous materials, while, Figs. 2 and 3 showed all model components after meshing separately and after assembly.

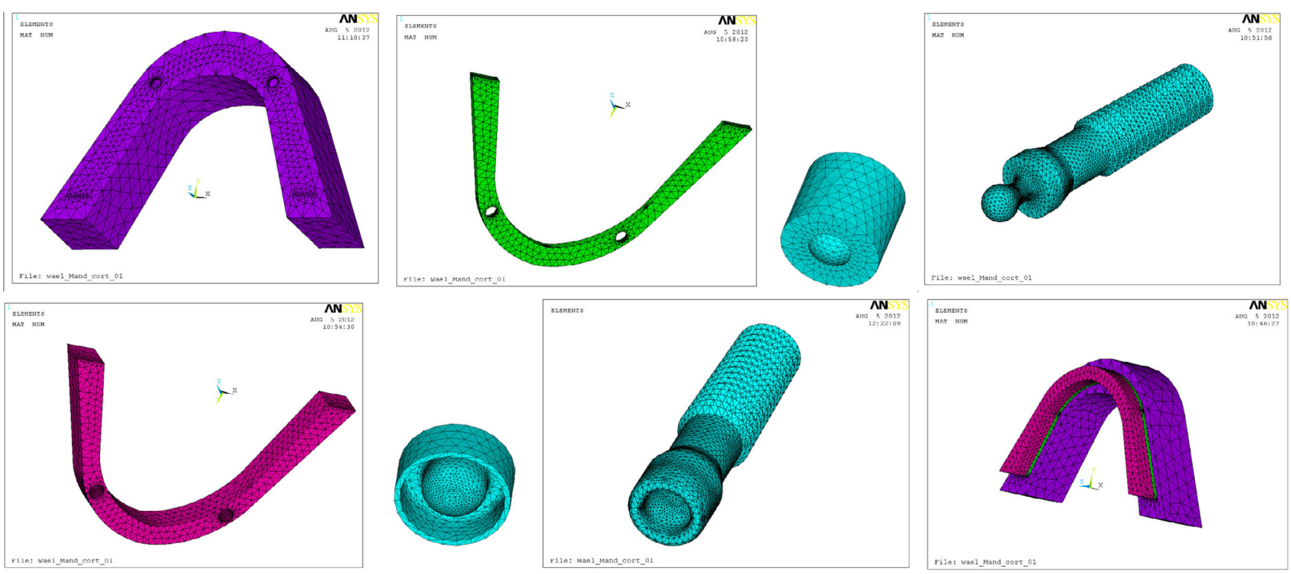

Figure 2 Meshing details of ball and socket and locator models.

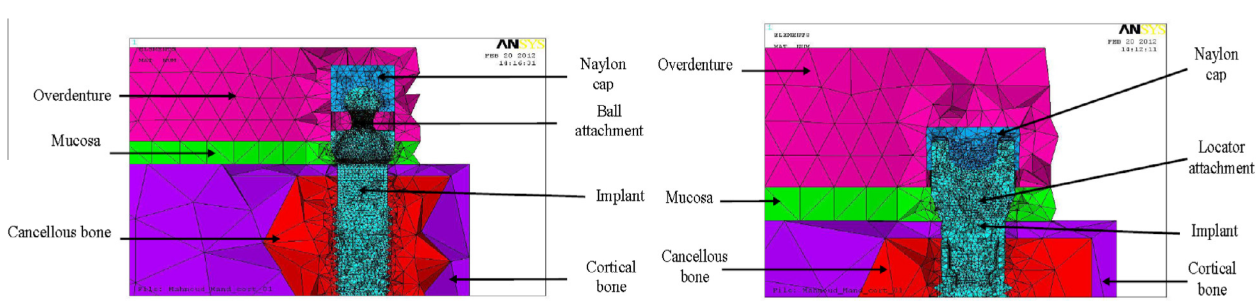

Figure 3 Implant, ball and socket, and locator models on ANSYS Screen, showing different component materials (as colors).

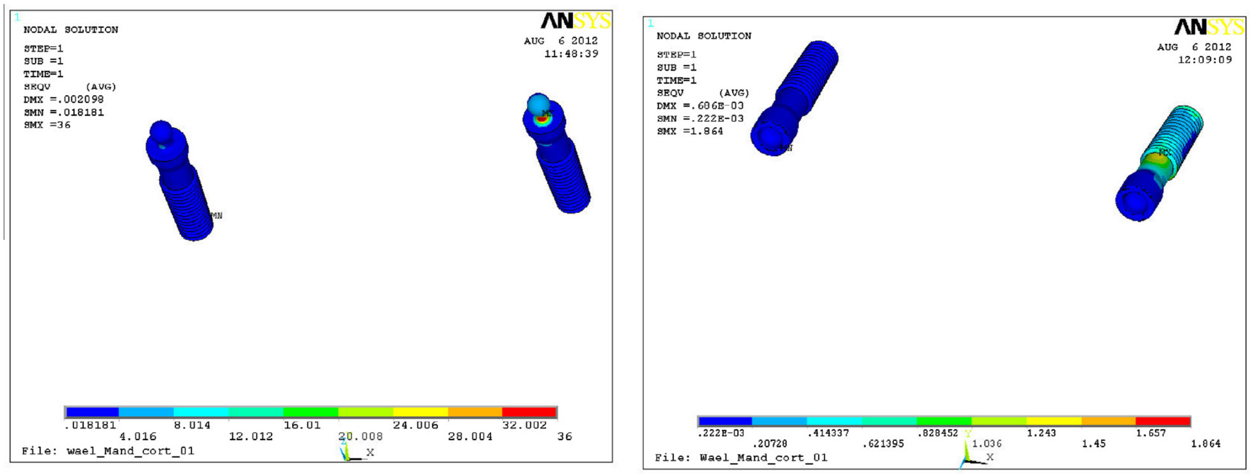

Figure 4 Von Mises stress generated on implant, ball and socket, and locator under 150 N.

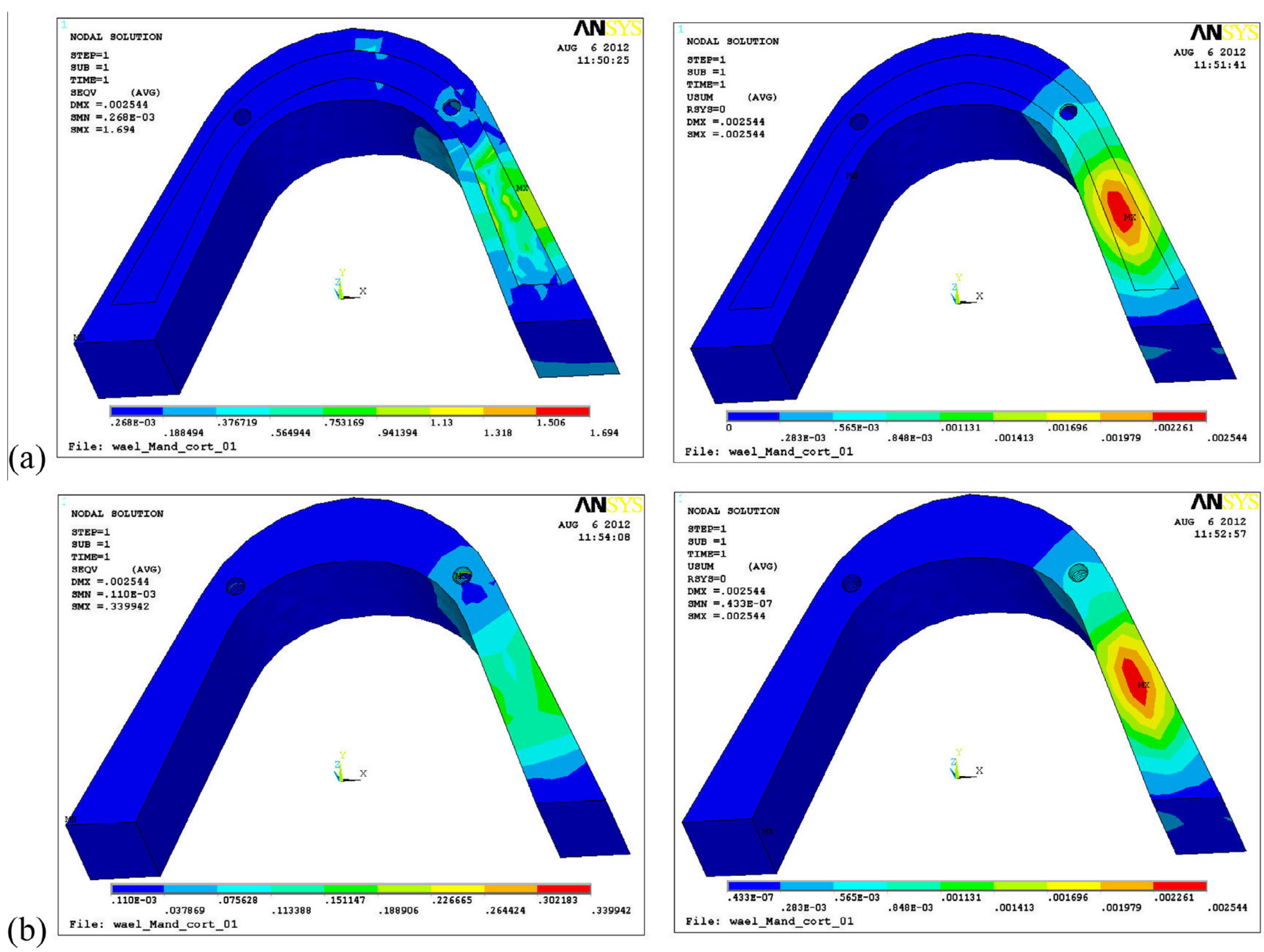

Figure 5 (a) Cortical and (b) spongy bone Von Mises stress and total deformation under vertical load of 150 N respectively with ball attachment.

Unilateral masticatory compressive loads of 50, 100, and 150 N were applied to the overdentures, in a vertical direction, parallel to the longitudinal axes of the implants. Loads were directed separately toward the central fossa in the molar region of each overdenture. Where, the results obtained with 150-N loading were presented graphically and compared as the worst-case conditions. Linear static analysis was performed using a personal computer (Intel Core to Duo processor, 2.8 GHz, 4.0 GB RAM).

3. Results

Analysis of vertical loading demonstrated an uneven stress distribution pattern on the implant–abutment complex, prosthetic appliance, and supporting structures around the loaded implants. Figs. 4–6 demonstrated the Von Mises stress and total deformation distribution patterns on the different components of the two models under the worst expected loading 150-N as a graphical comparison.

As illustrated in Fig. 4a, the maximum Von Mises stress induced on implants with ball attachments was 36 MPa, and was concentrated at the neck of the ball abutment on the load application side, while minimum Von Mises stress induced on these implant complexes was located on the labial aspect of the ball abutment neck on the side opposite load application. Similarly in Fig. 4b, maximum Von Mises stress induced on implants with locator attachments was 1.86 MPa (about 18 times less value in comparison to ball attachment), and was concentrated in the cervical portion of the implant fixture on the load application side. Fig. 5 showed ball and socket model results that Von Mises stress distribution on cortical and cancellous bone layers over the entire alveolar ridge where the maximum values on cortical bone, cancellous bone, and mucosa were 1.69, 0.34, and 0.55 MPa, respectively. The high Von Mises stress values were concentrated at the crest of the cortical bone and mucosa at the load application site. Maximum Von Mises stress induced in cancellous bone was located at the bone–implant interface on the load application side. Minimal stresses induced in cortical and cancellous bone were located in the most distal region of the mandible on the side opposite load application. Minimal Von Mises stress induced in mucosa was located around the implant on the non-loaded side.

Results with using locator attachments (presented in Fig. 6) showed that the induced maximum Von Mises stresses in cortical bone, cancellous bone, and mucosa of 2.09, 0.22, and 0.77 MPa, respectively. The maximum Von Mises stress was located at the crest of the cortical bone at the load application site. In cancellous bone, maximum Von Mises stress was located at the bone–implant interface on the load applications. Maximum Von Mises stress in the mucosa was concentrated at the center of the alveolar ridge mesial to the point of load application. Minimal Von Mises stress in cortical bone was located in the distal region of the mandible on the side opposite load application. In cancellous bone, minimal Von Mises stress was mesial to the implant of the side opposite load application. Minimal stress in mucosa was located around the implant on the non-loaded side.

Total deformation results in cortical bone, cancellous bone, and mucosa (lower parts of the ball and socket attachment model) were less by about 12%, 12%, and 21% respectively, in comparison to the locator attachment model. Similarly, Von Mises stresses in cortical bone and mucosa demonstrated the superiority of the ball and socket model by ratios of 23% and 33%, respectively.

Von Mises stress results obtained on all components of the studied models are compared in Fig. 7, using the ball attachment results as a reference. Positive percentages thus indicate superiority of the locator

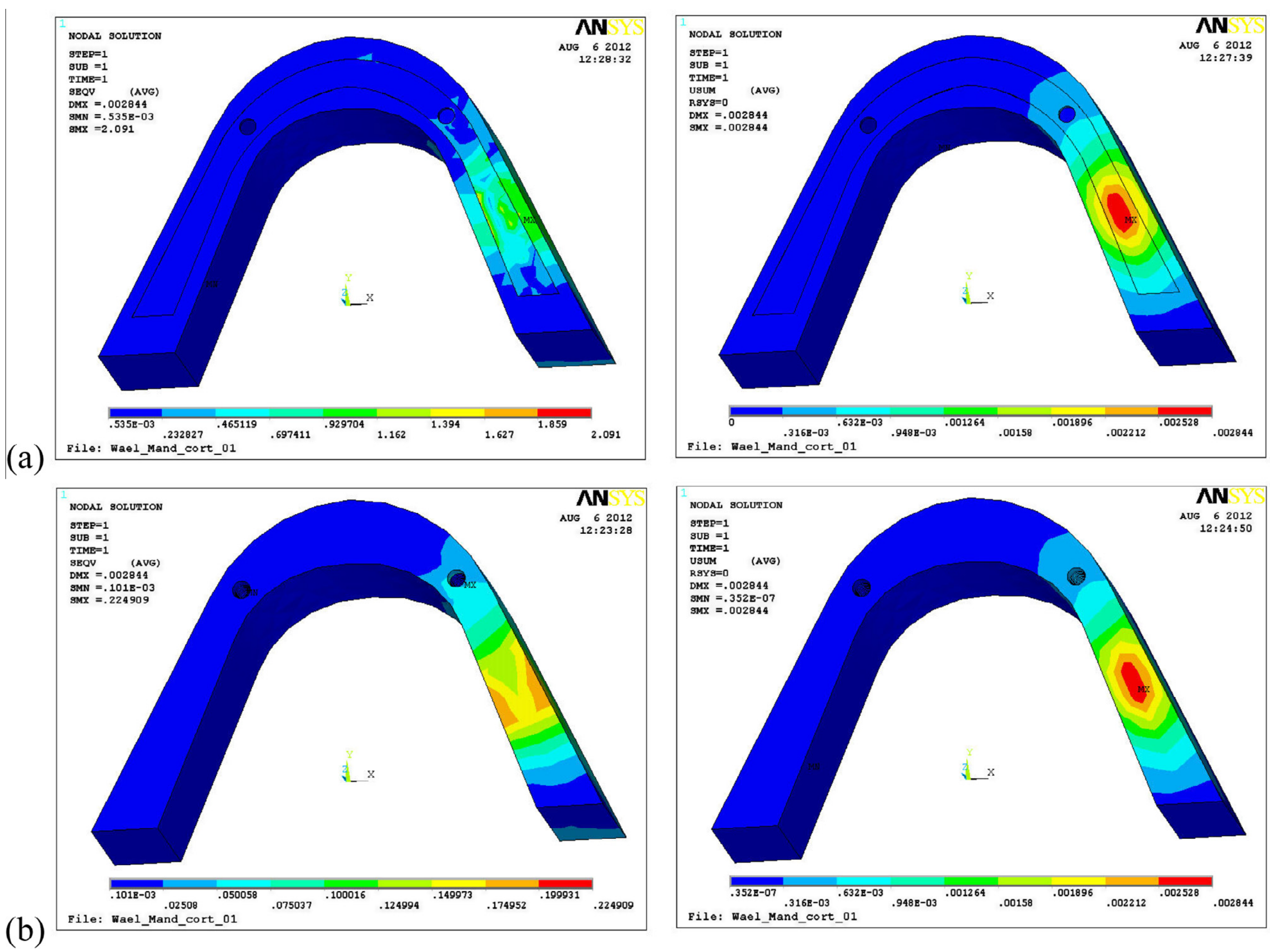

Figure 6 (a) Cortical and (b) spongy bone Von Mises stress and total deformation under vertical loads of 150 N using locator attachment.

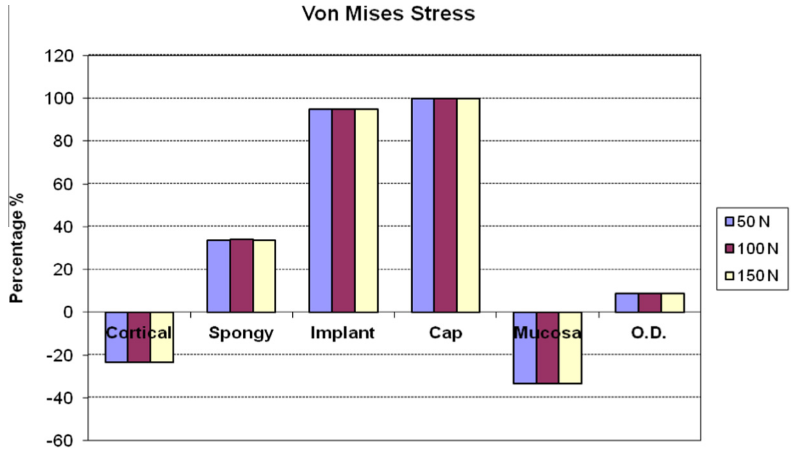

Figure 7 Von Mises comparison between ball and locator attachment results as percentage.

attachment over the ball and socket attachment). Although the ball and socket attachment seemed to show superior performance in cortical bone and mucosa, all Von Mises stress values for these elements were sufficiently low to indicate that the use of either attachment type is safe, when cortical and mucosal stress are the sole selection indicators/criteria. For components above the mucosa (overdenture, caps, and implants), the locator attachment model showed obviously superior performance relative to the ball and socket attachment model in terms of stress, as indicated by ratios of 9%, 100%, and 95%, respectively. These results reflect the dominance of bending stress, for which the wider neck of the locator attachment is better from mechanics point of view.

The same concept can be applied to total deformation, as performance at the caps and implants was much better in the locator attachment model than in the ball and socket model (ratios of 97% and 71%, respectively). In contrast, 18.5% less total deformation of the overdenture was observed in the ball and socket than in the locator attachment model.

4. Discussion

The discussion of study results should take into account load value and location with respect to implant complex location and attachment type. Loading in the molar area with a fixed implant in the canine area will result in complex stress tensors including tensile/compressive, shear, and bending stresses.

On comparing the stress patterns generated within the implant-attachment assemblies, the locator attachment provided lesser stress values at the implant–locator junction. This may be due to the smaller height and wider diameter of the Locator attachment than Ball attachment. This Geometrical design allows better dissipation of stresses that resulted on occlusal load application. (El-Taftazani et al., 2011). The obtained results in this study can be interpreted to reflect energy absorption by the attachment. The smaller neck of the ball and socket attachment enables greater energy absorption, which reduces the amount of energy (stress) transferred to the mucosa and cortical and cancellous bone.

In contrast, 34% less stress in cancellous bone was observed in the locator attachment model than in the ball and socket attachment model. This result is due to the low rigidity and stress transfer system of cancellous bone; cortical bone will resist and absorb more load energy than any other part of the lower system region (i.e., cancellous bone and mucosa). Maximum equivalent stresses in cortical bone and mucosa were 23% and 33% less, respectively, in the ball and socket attachment model than in the locator attachment model. Although these ratios between the two models appear to be very high, in reality the level of generated stresses are fairly low or may be negligible. Generally and in a single statement, the locator attachment can be considered superior to the ball and socket attachment in terms of prosthesis lifespan, while differences in effects on bone are negligible (Saleh, 2012; Omar, 2012).

5. Conclusions

Within the limitations of this study, the following conclusions can be derived:

Von Mises stress on overdentures was about 9% less in the locator attachment model than in the ball attachment model, indicating that locator attachments lead to longer prosthesis life, on the other hand, the ball attachment model showed superior performance in the mucosa, with 20% and 33% less deformation and Von Mises stress, respectively.

The locator attachment model showed superior performance in caps, with 99% and 100% less deformation and Von Mises stress, respectively. These results indicate a longer cap lifespan with more time between successive maintenance sessions. In addition, it showed superior performance in implants, with 80% and 90% less deformation and Von Mises stress, respectively.

Cortical bone received 12% and 23% less deformation and Von Mises stress, respectively, in the ball attachment model than in the locator attachment model. While, cancellous bone received 33% less Von Mises stress but showed 12% more total deformation in the locator attachment model.

Generally, in the context of vertical loading in the molar area of an overdenture, ball attachments are preferable for weak bone and locator attachments ensure longer cap and overdenture life.

Ethical approval

This research did not work on humans and does not require ethical approval and followed the Helsinki declaration.

Conflict of interest

The authors declare that they have no conflict of interest.

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